









**The MACHO Project SMC Variable Star Inventory. I. The
Second-overtone Mode of Cepheid Pulsation From First/Second
Overtone (1H/2H) Beat Cepheids**

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ABSTRACT

We report the discovery of 20 1H/2H and 7 F/1H beat Cepheids in the SMC by the MACHO Project. We utilize the 20 1H/2H stars to determine lightcurve shape for the SMC second-overtone (2H) mode of Cepheid pulsation. We predict, similar to the findings of Alcock *et al.* [1997, ApJ, submitted], that 2H Cepheids will have nearly or purely sinusoidal light variations; that the P – L relation for 2H Cepheids will not be distinguishable from the P – L relation for 1H Cepheids within photometric accuracy; and that 2H stars may be discernable from F and 1H stars using the amplitude-period diagram and Fourier parameter progressions for periods $P \lesssim 0.7$ days, our current sample 2H period limit.

Subject headings: Cepheids — Magellanic Clouds — stars: fundamental parameters — stars: oscillations

1. Introduction

The second-overtone (2H) mode of Cepheid pulsation has been predicted to exist theoretically since Stobie (1969a, 1969b)’s pioneering investigations. Yet, since then, we have found only scant evidence for 2H mode excitation in our Galaxy. CO Aur was recognized as a first-overtone/second-overtone (1H/2H) beat Cepheid by Mantegazza (1983), and later confirmed as such by various studies (*e.g.*, Antonello & Mantegazza 1984; Babel & Burki 1987). On the other hand, HR 7308 is a proposed singly-periodic 2H Cepheid whose modal status remains uncertain, despite many investigations (Burki *et al.* 1986; Fabregat, Suso, & Reglero 1990; Simon 1985; Bersier 1996; Bersier & Burki 1996). This paucity of Galactic 2H Cepheids is not unexpected. From a theoretical standpoint, Galactic 2H Cepheids should have low masses and luminosities (Chiosi, Wood & Capitano 1993). As well, they are expected to be the shortest-period Cepheids at a given luminosity (Chiosi *et al.* 1993), so that they should appear in greater frequency in lower metallicity environments than our own (see *e.g.*, the period frequency distributions of Cepheids in Lipunova 1992). Observationally, in our own galaxy, CO Aur’s semi-amplitude of pulsation for its 2H mode is only 0.043 ± 0.002 mag (Pardo & Poretti 1996)—so that, even if we observe these faint stars, we might not detect their variability.

The advent of large-scale astronomical surveys has improved our chances of observing 2H Cepheids. As by-products of gravitational microlensing searches in the Galactic bulge and Magellanic Clouds, the MACHO and EROS Collaborations have found 45 1H/2H and at least 37 F/1H beat Cepheids in the LMC (Alcock *et al.* 1995, 1997; Beaulieu *et al.* 1997), and 27 1H/2H and 10 F/1H beats (counting this work and Beaulieu *et al.* 1997) in the SMC to date. Concurrent analyses of these, and other findings, has allowed investigations of the 2H mode of Cepheid pulsation. Pardo & Poretti (1996) re-analyzed the composite lightcurve of CO Aur, the sole 1H/2H beat Cepheid in the Galaxy, and noted that its 2H

mode appeared as a purely sinusoidal light variation. Alcock *et al.* (1997) analyzed 45 first-overtone/second-overtone beat Cepheids in the LMC, showing (1) that the 2H mode resulted in sinusoidal, or nearly sinusoidal ($0 \leq R_{21} \lesssim 0.2$) lightcurves¹; (2) that LMC 2H Cepheids could be distinguished from LMC 1H and F Cepheids in Fourier space for $P \lesssim 1.4$ days; (3) that 2H Cepheids should overlap the short-period edge of the 1H P – L sequence; and (4) that the location of 2H pulsators in the $\log L$ – $\log T_{\text{eff}}$ plane depended significantly on the adopted M – L relation, and would have to come from observation. Finally, Antonello & Kanbur (1997) have investigated the 2H mode of Cepheid pulsation by non-linear pulsation models appropriate to the LMC ($Z \approx 0.01$). They confirmed that 2H Cepheids should be more numerous for lower metallicities, and produced theoretical R_{21} – P sequences which agreed qualitatively with the sequences for LMC 1H/2H beat Cepheids in Welch *et al.* (1997). They also predicted a resonance of the R_{21} – P and ϕ_{21} – P sequences near $P = 1$ day.

With the recent reduction of SMC photometry by the MACHO project, we are in a position to add to our knowledge of the 2H mode. We report the discovery of 20 1H/2H beat Cepheids in the SMC (distinct from the stars in Beaulieu *et al.* 1997), and their implications for the 2H mode of Cepheid pulsation. We compare our findings to the 2H mode characterizations in the LMC and Galaxy to date, and provide guidance on how to discern 2H from F and 1H Cepheids.

¹ $R_{k1} = V_k/V_1$ is the relative amplitude of the first harmonic and ‘base’ frequency model amplitudes in a truncated Fourier series $V(t) = V_0 + \sum_{k=1}^{\mathcal{O}} V_k \cos(2\pi k \nu t + \phi_k)$, while the phase difference $\phi_{k1} = \phi_k - k\phi_1$. For beat Cepheids, R_{21} and ϕ_{21} are calculated for each mode of pulsation.

2. Observations and Analysis

We refer the reader to Alcock *et al.* (1995) for a description of our two-bandpass photometry (the MACHO V and R bands) and beat Cepheid identification process. The beat Cepheids reported in this paper were selected by our alert system software and not by a full analysis run. Therefore, the total number of beat Cepheids in these fields is likely to be $4\text{--}5 \times$ greater than reported here. To be identified as an alert, a star must be 7 sigma brighter than the template and have increased in brightness by at least 0.35 mag. SMC observations of these Cepheids span 3 years; lightcurves consist of anywhere from 163–1306 observations, which are free of possible cosmic ray events, bad or missing pixels, or data suffering from poor image quality. This paper utilizes MACHO V -band photometry for all results.

We subjected each star to our coding of the CLEANest algorithm (Foster 1995, 1996a, 1996b) for joint frequency analysis and lightcurve modelling. This method avoids having to choose a truncated Fourier series order *a priori*, as discussed in Pardo & Poretti (1997) and Alcock *et al.* (1997). Briefly, CLEANest uses the date-compensated discrete Fourier transform (DCDFT) of Ferraz-Mello (1981) on a time series to produce a power spectrum for test frequencies from $\nu_{\text{res}} = (2T_{\text{span}})^{-1}$ to $\nu_{\text{max}} = (2\min(\Delta t))^{-1}$ in steps of ν_{res} (the frequency resolution), where T_{span} is the total timespan of the observations for a star, and Δt the time separation between successive observations. If any of the frequencies in the power spectrum are adopted as significant, they are modeled by $\cos(2\pi\nu t)$ and $\sin(2\pi\nu t)$ terms (plus a constant) as in Foster (1995). The resultant model is subtracted from the data, these *residuals* are subjected to another DCDFT, and the process is iterated until no significant frequencies remain. Each time a DCDFT of the data or residuals has been performed, CLEANest seeks to find the n -tuple of frequencies which gives the best description of the data. Operationally, frequency space is searched for frequencies in the

neighbourhood of the currently adopted ones for a maximum of Foster (1996a, 1996b)’s model amplitude.

In all cases, the 1H mode frequency, ν_{1H} , appeared as the peak frequency in the first power spectrum, generally followed either by $2\nu_{1H}$ or ν_{2H} . We confirmed the identity of ν_{1H} and ν_{2H} by requiring $\nu_{1H}/\nu_{2H} \sim 0.805$, as found in Alcock *et al.* (1995). After these frequencies were discovered, we adopted a frequency as significant if it was a linear combination of ν_{1H} and ν_{2H} ; if it appeared as one of the 20 most powerful frequencies in a residual spectrum; *and* if it was reasonable (*i.e.*, we would not have modeled a frequency that seemed to be $2\nu_{1H} + \nu_{2H}$ if we had not previously detected $2\nu_{1H}$ or ν_{2H} in our analysis), as discussed in Alcock *et al.* (1997). For some stars we had to adopt a frequency close to 1.003 day^{-1} (*i.e.*, the frequency corresponding to one sidereal day) in the modeling process, because of the scheduling of observations. When no remaining significant frequencies could be detected, we discontinued modeling with CLEANest, and subjected the fits to the Marquardt algorithm² for improvement, at no point restricting our model frequencies to obey their expected relations to ν_{1H} and ν_{2H} : *i.e.*, all frequencies were varied by both CLEANest and the Marquardt algorithm independently of ν_{1H} or ν_{2H} themselves. This was done as a check on the robustness and identity of a given frequency.

In Table 1, we present periods and period ratios for our 27 SMC beat Cepheids. P_L is the ‘long’ period, while P_S is the ‘short’ period, of pulsation. For F/1H stars ($P_S/P_L \sim 0.73$), $P_L = P_F$ and $P_S = P_{1H}$; for 1H/2H stars ($P_S/P_L \sim 0.805$), $P_L = P_{1H}$ and $P_S = P_{2H}$. Uncertainties in the last three digits of periods and period ratios have been placed in

²The Marquardt algorithm is a χ^2 minimization method which pragmatically alternates between a ‘steepest descent’ (or gradient-search) algorithm when χ^2 changes rapidly near a given set of model parameters, and a first-order model expansion when χ^2 changes little near a set of model parameters (see *e.g.*, Bevington & Robinson 1992).

parentheses; uncertainties in the period ratios were obtained from the uncertainties in P_L and P_S .

3. Results and Discussion

3.1. The Petersen Diagram

We have plotted the Petersen diagram for all of our SMC beat Cepheids and the 45 LMC 1H/2H beat Cepheids of Alcock *et al.* (1997) as Figure 1. We note the LMC and SMC 1H/2H beat Cepheids have essentially the same progression of period ratio P_{2H}/P_{1H} versus P_{1H} despite differences in host galaxy metallicity. This was borne out in the linear, non-adiabatic calculations of Morgan & Welch (1996), who predicted little or no noticeable shift in P_{2H}/P_{1H} from the LMC to SMC. Observationally, this similarity in period ratio was also noted by Beaulieu *et al.* (1997) by comparing their 7 SMC 1H/2H beat Cepheids with the 15 1H/2H beat Cepheids of Alcock *et al.* (1995).

3.2. The Bailey Diagram

The Bailey (or Period-amplitude) diagram for the 1H/2H beat Cepheids of this paper and Alcock *et al.* (1997) is presented as Figure 2. The amplitude Δ is the model semi-amplitude for the base Fourier term of a mode of pulsation. We see that, in general, $\Delta_{2H} \lesssim 0.10$ mag, while $\Delta_{1H} \gtrsim 0.11$ mag, although this is not always the case: there is a star with $\Delta_{2H} = 0.105$ mag in the SMC, and a star with $\Delta_{1H} = 0.071$ mag in the LMC in the Figure. Similar conclusions can be drawn from Figure 3 of Beaulieu *et al.* (1997), who found SMC 2H mode amplitudes less than 0.08 mag, and 1H mode amplitudes of 0.12 mag for similar periods. Clearly, the 2H mode results in a low pulsation amplitude.

3.3. Fourier Parameter Sequences and 2H Mode Lightcurve Shape

We detected the second harmonic of the 2H mode frequency, $2\nu_{2H}$, for 6 of 20 stars, but found this frequency remained stable (*i.e.*, differed by more than twice its formal uncertainty from twice ν_{1H}) in the Marquardt improvement for only 2 of these 6 stars. This is contrary to the LMC beats analyzed by Alcock *et al.* (1997): all 8 of 45 stars that had $2\nu_{2H}$ detected also had that frequency remain stable over Marquardt improvement. This may suggest $2\nu_{2H}$ detections here are of a more marginal nature than in the LMC, owing to the SMC’s greater distance modulus ($\mu_{\text{SMC}} - \mu_{\text{LMC}} \sim 0.5 - 0.7$ mag; Feast 1988, 1989), and thus fainter stars, although SMC exposures were twice as long as LMC exposures to compensate.

No second ($3\nu_{2H}$) or higher harmonics were detected in any of our sample for the 2H mode, limiting us to R_{21} and ϕ_{21} to describe its lightcurve shape. For the 1H mode, frequencies up to the third harmonic, $4\nu_{1H}$, were detected; the higher order $R_{31} - R_{41}$ and $\phi_{31} - \phi_{41}$ for the 1H mode will be presented in a future paper.

Fourier parameters for those stars with detected, stable harmonics in our CLEANest–Marquardt scheme are presented in Figure 3. According to this Figure, 2 of 20 1H/2H beat Cepheids have nearly sinusoidal lightcurves for their 2H modes, while the remaining 18 have 2H modes that result in purely sinusoidal light variations: *i.e.*, $R_{21} = 0$, as shown in the Figure.

The stable $2\nu_{2H}$ frequencies in the LMC 1H/2H beat Cepheids of Alcock *et al.* (1997) were what prompted us to draw out 2H mode information from the LMC sample. We would like to gather as much information as possible on the 2H mode here as well. To circumvent stability concerns with $2\nu_{2H}$ frequencies, we have adopted a first harmonic term for each 1H/2H star’s model, and fit it to our data while holding its frequency to its expected value of $2\nu_{2H}$. No other frequencies were held to their expected identities, as they

retained their relationships to ν_{1H} and ν_{2H} throughout. We display the resulting Fourier parameter sequences in Figure 4 for those stars with $\sigma_{R_{21}} < 0.05$, which omitted 3 of 20 stars. The conclusions from either Figure 3 or 4 are the same: in general, the 2H mode is more sinusoidal than the 1H mode (from R_{21}). The scatter in ϕ_{21} prevents further comment.

4. Discerning 2H Cepheids

We do not yet have the luxury of a large SMC sample of Fourier-decomposed Cepheids on the same photometric system—or transformations to standard systems for the SMC—to compare our R_{21} – P and ϕ_{21} – P diagrams against. Our sample of beat Cepheids also constitutes a ‘first-order’ search through our developing SMC photometry database, and so cannot be claimed as complete. This is the first large sample of SMC beat Cepheids, however, so we should use them to make some statements about the SMC 2H mode.

Firstly, we note Figure 1 and Table 1 show the 1H and 2H P – L relations will be separated by less than $\log(P_{2H}/P_{1H}) = \log 0.80 \simeq -0.10$ in the SMC. Alcock *et al.* (1995) noted that this separation could well vanish due to observational uncertainties, overlapping the 2H and 1H P – L sequences. This suggests separation of SMC 1H and 2H mode Cepheids based on P – L position alone is not feasible.

Alcock *et al.* (1997) used the analytical fits to linear nonadiabatic pulsation calculations of Chiosi *et al.* (1993) to see how the boundaries of the instability strip (IS) and P – L relations in the LMC were affected by the choice of M – L relation. They chose to use the evolutionary M – L relation from mild core-overshoot models of Chiosi *et al.* (1993) and the empirical M – L relation of Simon (1990), and found that (1) relative positions for the F, 1H and 2H modes in the IS are markedly affected by the adopted M – L relation, so that the positions of 2H pulsators in the IS (or CMD) will have to come from observation; while

(2) relative P – L positions for the F, 1H and 2H modes remain, from shortest to longest period at a given luminosity: 2H, then 1H and F mode pulsators. These same conclusions hold for the SMC, using the same M – L relations and compositions of $Y = 0.30$, $Z = 0.004$: we reproduce the same trends and general positions of mode boundaries as Figures 1-4 of Alcock *et al.* (1997).

Fourier parameters provide better distinction than P – L or IS position between the 1H and 2H modes in the SMC. Figure 3 shows, as already found for the 2H mode of Cepheid pulsation in the LMC, that 2H Cepheids will have nearly, or purely, sinusoidal light variations, which should allow them to be discerned from 1H and F mode stars. The period-amplitude diagram (Figure 2) should provide further support for a 1H-2H mode distinction. This, of course, ignores sources of contamination, such as foreground W Ursa Majoris stars (*e.g.*, Kaluzny, Thompson & Krzeminski 1997), which can have nearly sinusoidal light variations and yet may occupy the same CMD and P – L regions as SMC or LMC Cepheids. Given a *bona fide* Cepheid, however, we should—with some certainty—be able to discern in which mode it pulsates from the information available to us.

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Fig. 1.— The Petersen diagram for all 27 MACHO Project SMC beat Cepheids, as well as the 45 1H/2H LMC beat Cepheids of Alcock *et al.* (1997). The upper sequence is P_{2H}/P_{1H} vs. P_{1H} , while the lower sequence is P_{1H}/P_F vs. P_F .

Fig. 2.— Amplitude-period diagram for 1H/2H beat Cepheids in the Magellanic Clouds from MACHO Project data. Δ is the model semi-amplitude of the base Fourier term for each of the 1H (open points) and 2H (filled points) modes.

Fig. 3.— Fourier parameters for the 1H, 2H, and F modes of pulsation from 27 SMC beat Cepheids..

Fig. 4.— Fourier parameters for the 20 SMC 1H/2H beat Cepheids when fitted by a first harmonic term for the 2H mode. Stars with $\sigma_{R_{21}} < 0.05$ are not shown.

TABLE 1. SMC Beat Cepheid Periods and Period Ratios

Cepheid ^a	ID ^b	P_L (days)	P_S (days)	P_S/P_L	Modes (L/S)
MACHO*01:06:17.7-72:24:43	206.17001..62	2.285683(214)	1.670634(157)	0.730913(097)	F/1H
MACHO*00:53:13.8-72:52:43	207.16139..99	2.180226(134)	1.587077(097)	0.727942(063)	F/1H
MACHO*00:46:37.0-72:25:30	208.15746..21	2.088145(179)	1.526433(131)	0.731000(089)	F/1H
MACHO*00:52:11.1-72:55:30	208.16081.114	2.020733(167)	1.475390(122)	0.730126(086)	F/1H
MACHO*00:41:28.7-73:22:60	213.15447..72	1.790251(131)	1.314105(205)	0.734034(127)	F/1H
MACHO*00:51:57.9-72:40:39	208.16085.137	1.662469(113)	1.221140(083)	0.734534(071)	F/1H
MACHO*00:56:17.4-73:25:51	211.16358.110	1.316132(060)	0.967952(225)	0.735452(174)	F/1H
MACHO*00:38:15.0-72:55:34	213.15226..51	0.871538(022)	0.700048(017)	0.803233(028)	1H/2H
MACHO*00:36:51.3-73:14:43	213.15164..68	0.854553(047)	0.687528(020)	0.804547(050)	1H/2H
MACHO*00:42:13.3-73:13:10	213.15449.141	0.842669(020)	0.677184(016)	0.803618(027)	1H/2H
MACHO*00:47:21.0-73:31:26	212.15787.140	0.830938(082)	0.668767(016)	0.804835(082)	1H/2H
MACHO*00:47:08.2-73:23:54	212.15789.168	0.739246(016)	0.595739(013)	0.805874(024)	1H/2H
MACHO*00:57:27.0-73:04:39	211.16421.152	0.738283(019)	0.595211(015)	0.806210(029)	1H/2H
MACHO*00:53:44.6-73:12:53	212.16191.275	0.728340(015)	0.586711(012)	0.805546(024)	1H/2H
MACHO*00:57:57.8-72:38:08	207.16484.287	0.715381(033)	0.576966(014)	0.806516(042)	1H/2H
MACHO*00:52:55.5-72:59:18	212.16137.372	0.713916(015)	0.575530(012)	0.806159(023)	1H/2H
MACHO*00:42:55.9-73:18:25	213.15505.230	0.705826(014)	0.569391(011)	0.806701(023)	1H/2H
MACHO*00:59:11.9-72:55:17	207.16537.170	0.700299(017)	0.564929(014)	0.806698(027)	1H/2H
MACHO*00:43:07.9-73:03:41	213.15509.194	0.677058(016)	0.546355(014)	0.806954(028)	1H/2H
MACHO*00:39:33.6-73:01:26	213.15281.105	0.674940(013)	0.543592(010)	0.805393(022)	1H/2H
MACHO*00:48:59.2-72:44:01	208.15913.220	0.658096(021)	0.530424(017)	0.805998(036)	1H/2H
MACHO*00:47:54.1-72:24:10	208.15861..16	0.657070(021)	0.529606(020)	0.806011(040)	1H/2H
MACHO*00:51:22.1-72:36:53	208.16029.122	0.647314(012)	0.521702(014)	0.805948(027)	1H/2H
MACHO*00:47:12.9-72:31:17	208.15802.110	0.638670(020)	0.514907(016)	0.806217(035)	1H/2H
MACHO*01:02:19.8-72:51:48	211.16709.152	0.611274(011)	0.492913(013)	0.806371(026)	1H/2H
MACHO*00:48:00.1-73:31:50	212.15844.246	0.609857(081)	0.491817(009)	0.806446(108)	1H/2H
MACHO*00:48:46.2-72:31:56	208.15916.211	0.592209(031)	0.477817(008)	0.806839(044)	1H/2H

^aObject designations follow MACHO Project convention: MACHO*, followed by an object's right ascension and declination (J2000.0).

^bThis column contains object designations internal to the MACHO Project.